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The expanding venue and persistence of planetary mobile robotic exploration—new technology concepts for Mars and beyond

Paul S. Schenker, Alberto Elfes, Jeffrey L. Hall, Terry L. Huntsberger,
Jack A. Jones, Brian H. Wilcox, and Wayne F. Zimmerman

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099
paul.s.schenker@jpl.nasa.gov
http://robotics.jpl.nasa.gov

ABSTRACT

The domain and technology of mobile robotic space exploration are fast moving from brief visits to benign Mars surface regions to more challenging terrain and sustained exploration. Further, the overall venue and concept of space robotic exploration are expanding—"from flatland to 3D"—from the surface, to sub-surface and aerial theatres on disparate large and small planetary bodies, including Mars, Venus, Titan, Europa, and small asteroids. These new space robotic system developments are being facilitated by concurrent, synergistic advances in software and hardware technologies for robotic mobility, particularly as regard on-board system autonomy and novel thermo-mechanical design. We outline these directions of emerging mobile science mission interest and technology enablement, including illustrative work at JPL on terrain-adaptive and multi-robot cooperative rover systems, aerobotic mobility, and subsurface ice explorers.

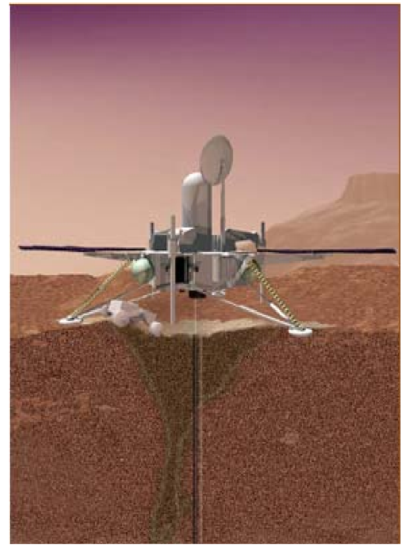
Keywords: space robotics, mobile robots, intelligent robots, robotic sensing, aerial robots, subsurface exploration

1. INTRODUCTION

In 1997, a small rover successfully explored a local 50 meter region about its Mars lander for a period of several weeks. This rover, the NASA Mars Pathfinder/Sojourner technology experiment, navigated its surrounding terrain by dead reckoning and short range hazard detection afforded by a laser/CCD sensor. Sojourner carried a single rear-mounted APXS (Alpha Proton X-Ray Spectrometer) instrument. The 2003 NASA Mars Exploration Rovers (MER)—launched almost concurrently with the British Beagle 2 lander—will attempt longer range regional mobile exploration over a period of several months in early CY04. The MERs and Beagle lander both carry multi-instrumented science with manipulative deployment, thus significantly enrichening *in situ* exploration opportunities. Later in this decade, NASA expects to launch a mobile Mars Science Laboratory mission that will operate for several years. The evolution of these rover systems is being driven by significant advances in autonomy—capabilities for multi-modal terrain perception, local area path planning, and on-board physical planning and controls for increasingly robust terrain traverse. Further, these technologies are beginning to evolve for aerial exploration of solar system bodies, e.g., for precision mapping, position estimation, science observation and thematic correlation, and potential aerial rendezvous with surface targets of interest. There is thus a general trend to extended surface coverage and increased persistence of operation that is being driven not only by advances in space avionics and on-board intelligence, but also by advances in surface, subsurface, and aerial physical (thermo-mechanical) architectures. This includes new rover designs that are opening up opportunities for Mars and Lunar high-risk, rough terrain access of great science opportunity. Beyond purely robotic missions lies the potential of sustained human/robot-teamed exploration and development of space. Examples of the previous, some of which we are currently conducting R&D proof of concept demonstrations for, include new smart reconfigurable rover systems for rough terrain traverse, networked multi-robot teams for planetary habitat preparation and large instrument deployments, aerobots for deep space exploration, icy melt subsurface explorers, and rovers based on altogether different design paradigms such as inflatable materials. We overview and illustrate representative paths of technology development, and describe some of the open problems. We begin with a brief overview of space robotic exploration objectives and issues, then cover the preceding topics on a section-by-section basis—advanced rovers, aerobots, and subsurface explorers.

1.1 Brief Background on Mobile Robotic Systems for Space

Space robotic systems span a wide range of applications, including their use in both *in-space assembly, maintenance and servicing*, as well as the *planetary exploration* focus of this paper. These two applications domains and their enabling technologies will certainly come closer as teamed human/robotic (H/R) exploration emerges, including precursor and actual H/R-resident science based missions. Ref. [1] provides a recent perspective of ongoing space robotics R&D. For purposes of this paper, the categories of mobile robotic systems and their potential venues of operation include:



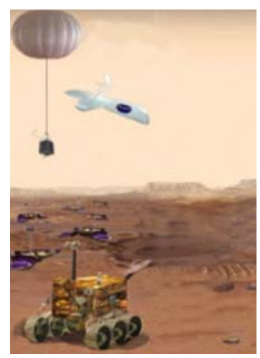
Aerial Systems (Venus, Mars, Jupiter, Saturn, Titan)
- Airplanes
- Balloons and blimps

Surface Systems (Mars, Europa, Titan)
- Science rovers (… beyond Mars)
- Advanced mobility systems (cliffs, craters, etc)
- Long-duration systems, cooperative assets, and robotic outposts

Sub-Surface Systems (Mars, Europa)
- Gravity penetrators
- Shallow and deep drills [see right **inset**]
- Burrowing devices/moles
- Directional melters, aquabots (deep ice/water)

Related Sample Acquisition & Handling (Mars, Europa, Titan, ...)
- Mobile manipulators for instrument and drill placement
- Precision rendezvous and transfers between mobility elements
- Sample exchanges between acquisition/*in situ* analysis systems
- Sample protection and containerization for sample return

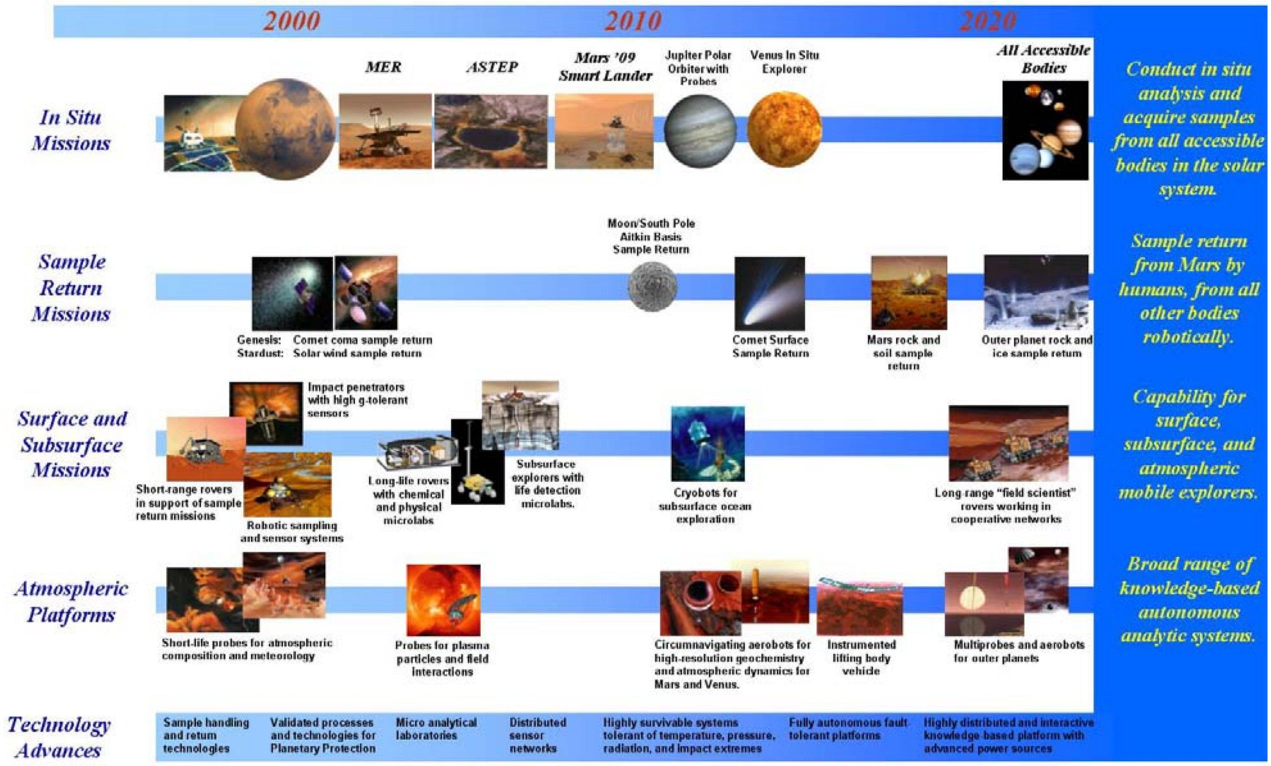
General goals for future mobile robotic exploration, in terms of enabling and enhancing science return are:



- Extend the range and duration of single missions
- Reduce uplink cycles per science target acquisition
- Enhance diversity of instrument deployment options
- Provide mobile access to more featured, adverse terrain
- Broaden surface payload landing options (hard/soft)
- Access disparate subsurface regions (soil/rock, ice/water)
- Span highly variable atmospheres (controlled ascent/descent)
- Return pristine surface & subsurface samples for earth analysis
- Coordinate aerial/surface/subsurface assets for global coverage [see right **inset**]
- Increase the fidelity of ground simulation, operations & science training
- Sustain—ultimately—a permanent networked robotic science presence …
- … and implement a meaningful partnership between humans & robots in space.

In terms of NASA mission development and priority directions for the above areas, the recent *Decadal report* [2] notes:

- Emphasis on Lunar Sample Return and Venus In Situ Explorer with expected technology feed-forward to later Mars and Venus sample returns
- Europa Geophysical Explorer as a precursor to a Europa Lander. Cassini-Huygens findings are expected to motivate a sequel Titan aerobot capability, which has figured prominently in NASA Code S planning to date.
- Technology drivers that include on-board autonomy, mobility mechanization & survivability, hard-to-reach mobile/manipulative sampling access, with system-related recommendations for supporting avionics advanced packaging and miniaturization
- The perspective of the Decadal survey is clearly one (given its requested ten year scope of recommendations) of advancing autonomous robotic capabilities for space exploration as a precursor to emplacing and sustaining a joint *human-robotic presence* at Lunar, Mars or other sites.



MANIPULATION

- EOA speed
- Accuracy
- Precision
- Dexterity
- Power efficiency
- Backdrive-ability
- Thermal stability
- Calibration

MOBILITY

- Ground speed
- Ground pressure
- Traversability
- Localization
- Cone of stability
- Climb rate
- Holonomicity
- Self-rightability

ON-BOARD INTELLIGENCE

- Resolution (multi-scale representation)
- Scalability (computational complexity)
- Completeness (search depth, breadth)
- Generalization (of classes, objects)
- Learning (from instances, training, etc.)
- Contingency (recursion, nonlinearity)
- Fidelity (binarization of analog models)
- Robustness (to partial, priced, and contaminated information …)

PERCEPTION

- Accuracy
- ROC (false positives)
- Calibration
- Weather and dust degradation
- Robustness (wrt. albedo, texture, etc.)
- Fidelity (of featural representation/recovery)
- Color and textural feature discrimination
- Generality (extrapolation, training, learning)
- Computation (Bits/Cycles for given function)

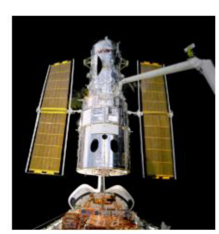


Figure 1: (top) A conceptual mission roadmap involving mobile robotic exploration; (bottom) Representative metrics for enabling robotics technologies (NOTE: This is neither a NASA program plan nor requirements for future NASA-funded R&D)

2.0 ADVANCED SURFACE MOBILTY SYSTEMS

There are several main lines of inquiry in planetary and small body surface mobility systems development [3]. The first is to provide rovers with *greater on-board autonomy* such that more diverse and productive science can be preformed in a given domain and duration. The second is to develop new rover concepts, leveraging autonomy, that enable rover *operation in more challenging domains*, e.g., extremely rough terrain. The third is development of *new physical rover architectur*es, involving basically different avionic/structural design and/or materials, per force overcoming conventional mass, volume, power and environmental limitations. We comment briefly on each line of development, illustrating some with highlights from R&D in our laboratories. See also the closing *Section 5* where we discuss cooperative multi-robot systems and human-robotic exploration.

2.1 Rover on-board autonomy

This area of work and its mission objectives is well illustrated by current NASA R&D programs for Mars Technology (http://mars.jpl.nasa.gov/technology/) and Intelligent Systems (http://is.arc.nasa.gov/), having work elements focused on automated mobility, manipulation, navigational guidance, and on-board reasoning (planning, scheduling, monitoring, fault recovery, etc.). Of particular interest to current mission development are automated *instrument placement* and *long range traverse*. The first function, in analogy with an earth field geologist, presumes a capability to quickly, accurately, and repeatedly place rover science instruments on highly variable targets a short distance away (5-to-10 meters) with controlled contact, possibly also extracting a drilled/cored sample and depositing it to containment or an in-field analysis tool. Current flight systems typically require 3-to-4 Martian sols to complete a ground target-designation-traverse-and-acquisition cycle. The desired improvement is to perform the entire sample designation-acquisition process in one command cycle—point to the target in calibrated downlink imagery, uplink this target (e.g., the feature location on a rock), and have the rover safely, accurately traverse and deploy its instrument into referenced surface normal contact or near proximity. This is likely implemented by visual closed-loop reference/servoing (feature tracking correlated with near-field stereo by hazard avoidance cameras) and perhaps force-accommodation guidance, or at least contact sensing. Overall, such an improvement has potential to significantly increase science return for a fixed duration mission. Current placement accuracy, for a typical one meter instrumented arm and NTSC stereo resolution is ~ 1 cm or more. It would also be desirable to improve this by a factor of five, thereby enabling precision scans and targeting of localized features. The second function, automation of long range traverse, again seeks to break the dependence on frequent Mars-to-Earth communication downlinks for rover state verification and trajectory planning (wherein more conventionally the rover performs only near field hazard detection and avoidance without ground state confirmation, and relies on ground science planners and operations personnel altogether for mid-range-and-beyond path planning and validation against frequently returned navigational camera imagery and rover state estimates). The goal is to reference a distant science target—one over-the-horizon (OTH) from direct rover observation—to rover coordinates via map imagery from descent-based, and/or multiple orbital observations. Given such information, on-board engineering state data as derived from multiple fused sources (e.g. odometry, accelerometry, inertial measurements/gyro, sun sensing), and iteratively updated external measurements of relative motion, the rover is to make a best *fused estimate* of its trajectory and current *localization* (position and pose) as it progresses. External measurement sources include visual odometry by visual feature tracking or optical flow, direct-sensed measurements (e.g., LIDAR), and/or longer range global landmark reference such as horizon feature tracking. Overall, the rover must robustly combine this information, and use it in combination with current trajectory planning/re-planning and obstacle avoidance to arrive at the final target (including the management of update feature maps in the rover reference frame for path planning). Traverse performance and accuracy can be highly variable in the absence of such automated navigation. Open loop traverse (dead-reckoned motion from rover wheel encoder data) often accumulates as much as 1-to-2 meters error over 10 meters in sandy washes. Wheel velocity synchronization (to compensate slip) can significantly improve this in more benign terrain. Integration of more common engineering data sources such as accelerometer/IMU data and global sun sensor data further helps, particularly when implemented under a statistical framework such as EKF fusion. Work to date suggests a longer range localization capability of 3-to-5% for distances of 10-to-100 meters, and in some very benign terrain, much better. However, much remains to be done for OTH traverse in more obstacle-strewn domains typified by VL1-VL2 (Viking Lander imagery) locales. Finally, we note that both of the above functions, instrument placement and long range traverse, have application to another mission goal beyond science acquisition—autonomous *sample return*, wherein a science rover may be required to perform a precision traverse to an awaiting lander and sample containment receptacle/ascent vehicle therein. This implies the capability to detect the distant lander, traverse 100 meters or greater distances, and rendezvous with accuracies of 1-2% in heading and position. See [3, 4] and references therein for recent representative developments in the above areas.

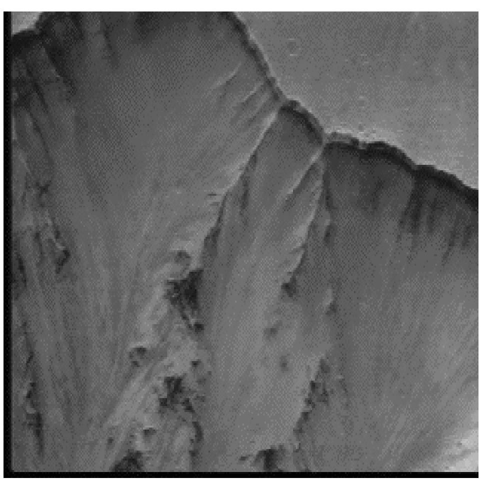
Work in the research areas of automated instrument placement, long range traverse, and sample acquisition and return figure prominently in rover field experimentation and science trials. Increasingly, rover R&D has moved to full scale prototypes and their long duration operation in realistic environments to validate both technology and mission operations concepts. Two examples are work of the *FIDO*-Field Integrated Design & Operations (http://fido.jpl.nasa.gov/) team with the MER flight project, and Carnegie-Mellon University's *NOMAD-II* Antarctic Meteorite Search task and related Atacama desert operations (http://www.frc.ri.cmu.edu/projects/meteorobot2000/)

Figure 2: Integrated terrestrial rover testbeds enable full scale technology validation in science relevant environments, thereby facilitating early infusion of products to mission use, as well as training of science personnel and verification of mission operations concepts. The rovers pictured at upper right in various field experiments are JPL's *FIDO* in simulated MER operations in the Mojave desert, CMU's *NOMAD-II* during meteorite field search, an automated in-field sample cache rendezvous and transfer between a science rover (JPL-*LSR*) and sample return rover (JPL-*SRR*), and finally, steep terrain access by the JPL-*Cliff-bot*.

2.2 Rover traversal of challenging terrain

Autonomous mobility over rough and hard-to-access terrain is a topic of both technical and applications interest in robotics. The technical challenges are considerable, as they span issues in mechanical design, sensing, planning, control, and underlying models and simulation of same. The potential applications are broad, one being rovers for the scientific exploration of solar system bodies (planets, moons, asteroids) with disparate surface characteristics and gravitation. Terrestrial applications include off- road vehicles for military and search & rescue functions. In a general sense, terrain is classified as "rough" and /or "challenging" as characterized by its progressive rock density, its variable, unpredictable surface properties (e.g., sandy, frangible, soft-dust-penetrable, icy), and steepness. Terrainability and traversability of mobile robots must be considered in context of scale and design. Among the approaches under consideration for rough terrain traverse are wheeled vehicles as well as tracked, modular-articulated, and less conventional uni-and-multiwheeled inflatable systems. Each have their respective strengths relative to particular domains and ranges of application—e.g., hard versus soft soil floatation properties, speed versus size, traversability relative to obstacle density and control complexity. Rover scale relative to terrain roughness, obstacle frequency, and obstacle size distribution also sets design constraints and performance criteria. E.g., smaller vehicles benefit from cube-square law effects (power, flotation), while larger vehicles finesse obstacles and rocky traverses by mechanical advantage. In summary, planetary mobility is a set of design trades between mechanical complexity/robustness, mass/volume/power resources, and computationally practical perception/control/planning that can detect, classify and mitigate obstacles and anomalies (as well as capture and maintain the necessarily accurate on-board, real-time model of vehicular state with respect to the surrounding terrain, examples being localization, pose, and wheel-soil interaction parameters). Planetary rovers are often quite limited in mass/volume/power resources and to date are largely of conventional wheeled design (cf., rocker-bogie mechanization of NASA/JPL's MPF-Sojourner '97 and MER/'03 vehicles, which do have near optimal obstacle clearance for a six wheel form factor). We have organized our rough terrain research at JPL (including collaborations with MIT colleagues, cf. S. Dubowsky) around *four related themes*, as surveyed in ref [5]: 1) physics-based mobility models for robust terrain traverse/interactions; 2) computationally-efficient, behavior-based control architectures that exploit these models; 3) rover designs having actively controlled, reconfigurable elements that improve agility/stability of traverse; and 4) extension of these concepts into networked and modular robotic systems that exploit collective estimation, distributed control, and coordinated multi-agent behaviors to perform tasks of larger, more complex scale. In this paper section we highlight aspects of themes 1-3), and later comment on theme 4) in the paper's final section.

Planetary rover operations have to date been in the context of low rock density terrains typified by Viking 1 and Mars nominal imagery—6-to-9% area density, and small scale rock outliers. Beyond this regime, approaching Viking 2 densities of 18 % and larger rocks, wheeled rovers of current scale (1 meter^2 length/track) confront problems of trapping, mean-free path obstruction, and in absence of robust sensing and hazard avoidance planning, also the risk of mission catastrophic upsets (by both positive and "negative" obstacles, that is, surface depressions). Thus, there is motivation to not only map and locally plan for obstacle avoidance, but also to enhance rover traverse capability by mechanical and sensory-control adaptation. Desired improvements are both quantitative and qualitative—rovers that drive more robustly through more variable VL1/VL2 Mars terrain, and new rover systems able to access increasingly difficult, steeply sloped regions of science importance. *Figure 3* shows examples of recent note in the space science community; it is thought that these sites will afford a rich developmental history of their formative processes through exposed strata of highly sloped terrains.



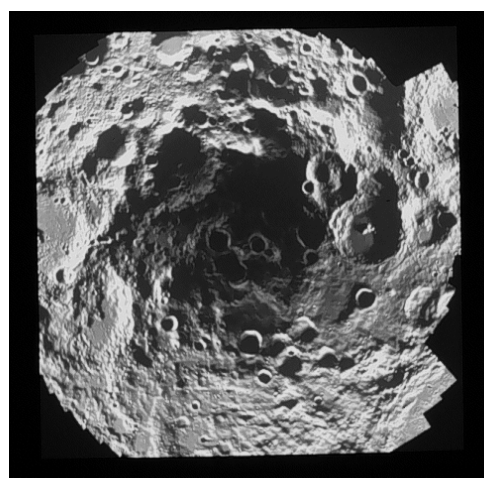


Figure 3: Examples of very challenging terrain of potentially great scientific importance—(left) Mars cliff-face with signs of water outflows, as observed by the Mars Odyssey orbiter (2001); (right) Lunar South Pole-Aitken Basin where signs of water were found by Clementine and Lunar Prospector

2.2.1 JPL All Terrain Explorer (*ATE*)

Figure 4 sketches operational scenarios related to rough terrain traverse. We have implemented such a concept, wherein a reconfigurable rover images its forward-looking terrain, derives a 3D terrain map from on-board stereo, analyzes terrain traversability with respect to predicted forward kinematics-and-quasistatic maneuverability/stability, and then sequences various *behaviors* that will optimize a rover stability performance metric. These behaviors are sequenced by a simple finite state machine on JPL's Sample Return Rover, reposing stance and c.g. This is done in two ways: by independent articulation of the rover shoulder strut angles, and by repositioning of the rover top-mounted robot arm. Per Figure 4, the arm is a reconfigurable resource for use in both kinematically unconstrained and closed-loop fashions. In the latter case, as yet un-implemented, the arm acts as a drive actuator, pivot point, or other element in rover-ground interactions, such as "de-trapping", direct stabilization, anchoring, etc. See [3] and references therein for details.

Posture and Mobility Modes ⇨ / Detectable/ Predictable Conditions ⇩	Center-of-Gravity Rebalance	Shoulder Raise/Lower	Arm Ground Contact	"Belly Down"	"Crabbing"	Join/Split & Tethering
Traction Loss	Visual Odometry & Wheel Current				Roll/Pitch Sensing & Wheel Current	
Steep Slope	Roll/Pitch Sensing & Range Map	Roll/Pitch Sensing & Range Map		Range Map	Roll/Pitch Sensing & Wheel Current	
Wheel Trap			Wheel Current			
Support Loss			Acceleration & Tilt Sensing			Acceleration & Tilt Sensing
Crevasse						Range Map
Tip Over			Roll/Pitch Sensing			

Figure 4: (left) Trigger Conditions for rover reconfiguration, wherein detection of these conditions leads to sequencing of a set of compensating behaviors in form of re-posing the rover for improved stability; (right) The All Terrain Explorer descending a 35-40+ degree slope, having differentially reposed its two shoulder joint angles and shifted its manipulator c.g. to regain near level ground stability

We do not incorporate rover dynamics, as they are not a contributory factor relative to the 5-to-10 cm/sec traverses typical of ATE operation. We do incorporate static friction-and-slip, treating this through the underlying kinematics and quasi-statics equilibrium analysis referred to surface-force contact models and an idealized Coulomb friction model. Complementing this *predictive* approach to rover reconfiguration, developed at JPL, is a *reactive* control approach developed by MIT with JPL wherein rover stability analysis is based on *instantaneous* internal state (engineering sensor pose and articulation data) and physically-based planning. This latter technique is very computationally efficient.

2.2.2 Inflatable rover technology

As noted in *Section 1*, there are strikingly different solutions and design trade spaces for planetary surface mobility. One such design space is inflatable systems, which have promise to be very light, fast, reasonably robust, and flight-stowable in a small fraction of their field-deployed volume. Trade-offs include potential long term leakage and vulnerability of the inflatable architecture, as well as yet-to-be-determined feasibility of precise sensor observations, instrument pointing and deployments from such non-rigid structure.

JPL has recently pursued the development of two types of inflatable rovers. The first is a mechanically-driven, multi-wheeled rover, as shown in *Figure 5*. The purpose of designing large, lightweight, inflatable wheels is to allow the rover to travel over rocks instead of around them, as present planetary rovers are required to do. This can greatly increase a rover's versatility, speed, and range. It has been estimated that in the 5% rockiest regions of Mars, approximately 1% of the surface is covered by rocks of 0.5 m or higher [6]. Early tests with scale models of inflatable rovers showed that this type of vehicle could easily scale rocks that were 1/3 the diameter of the wheels. Thus, a wheel size of 1.5-m diameter was chosen to allow the rover to traverse well over 99% of the Martian surface. In order to minimize mass and complexity, a three-wheeled vehicle was chosen with a wide wheelbase to enhance stability in rugged and steep terrain.

The second type of inflatable is a large wind-blown sphere, or “Tumbleweed”, with a central payload that is held in place by tension cords (*Figure 5*). A six-meter diameter Tumbleweed that has a mass of 10 kg plus a 10 kg payload will be capable of traveling over 1 m rocks and up 25 degree hills with typical winds of 20 m/sec during the Martian southern hemisphere summer. The multi-wheeled rover can travel at speeds of a few km/hr over very rocky terrain, while the wind-blown version travels at nearly the speed of the wind, or about 30-70 km/hr. The only control on the Tumbleweed is controlled stopping (deflation) and restarting (inflation with wind). The primary science objective for both types of inflatable rovers is to survey large areas of Mars in a relatively quick manner. Typical science instruments include visual imaging, a radar to detect subsurface water, a meteorological package, and surface and subsurface sampling equipment with possible GCMS capability to search for evidence of past or present life.

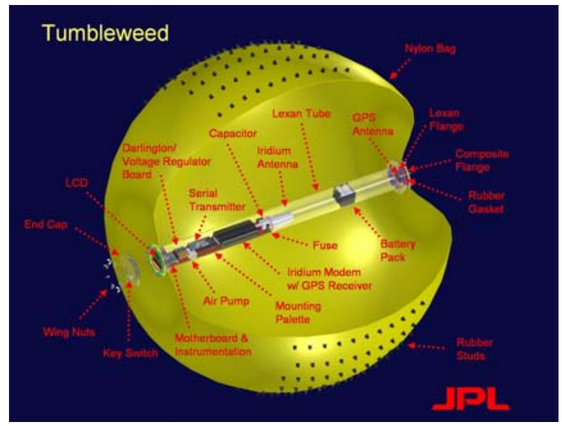


Figure 5: (left) Three-wheeled inflatable rover in field testing; (right) Design concept for Tumbleweed, for which a simple prototype is currently in field testing per a 2003 deployment from Summit Camp, Greenland.

JPL initiated work on the multi-wheeled Inflatable Rover in 1999 with a three-wheeled design that was tested in a wide variety of rocky, sandy, and liquid lakes, simulating those of Titan [7]; experimentation addressed use of both Kevlar and Spectra tires in a wide variety of rugged conditions. CMU, in collaboration with JPL, performed a number of parametric configuration studies, as well as successful 50 km endurance tests for the fabric wheels. Work on the windblown Tumbleweed began in 2001 [8]. Early tests took place in California’s Mojave Desert, and confirmed analytical mobility predictions. Current work seeks to perform a long-range, 1000 km endurance test on the glacial ice of Greenland [9]. Future work includes tests of direct landing capability (viz. without need of a parachute or retrorocket-assisted descent).

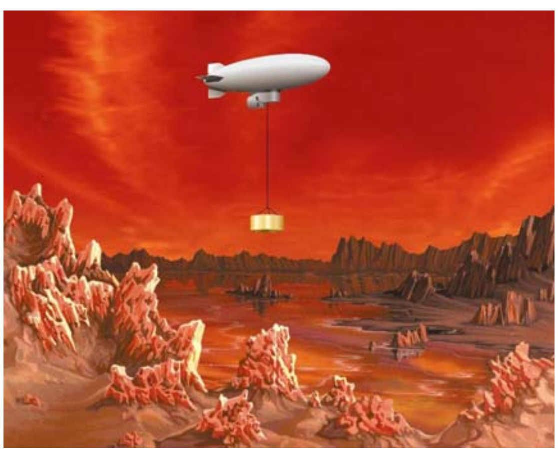
3.0 AEROBOTS

Planetary exploration to date has been primarily performed via fly-by or orbital probes such as the Voyager, Galileo, Cassini and Mars Odyssey spacecrafts. These are able to quickly and efficiently provide global, albeit limited-resolution surveys of planetary bodies. Additionally, severely restricted surface exploration has been performed by stationary landers such as the Viking probes or mobile robots, e.g., Sojourner rover. The strategic gap between orbital and ground systems can potentially be bridged through “aerobots”, robotic balloons and airships that provide low speed, low altitude sensing platforms for high resolution, wide area, controllable data acquisition and monitoring over any type of terrain and geographical site.

The bodies of the Solar System of immediate interest for aerobot exploration are Venus, Mars, and Titan. In the case of Titan, the earlier-noted Solar System Exploration Decadal Survey [2] identified a follow-on Titan mission as a high priority subsequent to Cassini-Huygens. Given that the top priority Titan science questions relate to the composition and distribution of organic material on the surface, this “Titan Explorer” mission will require an *in situ* vehicle that can make the required measurements. There are great opportunities for application of aerial mobility technology to post-Cassini-Huygens exploration of Titan. In particular, Titan's thick atmosphere enables the use of compact, self-propelled buoyant vehicles that can access most of the moon over multi-month time scales with minimal consumption of scarce onboard electrical power. These vehicles can provide science data that cannot be reasonably obtained through rovers or other types of vehicles. Aerobot technology development is thus seen as a priority within the NASA Solar System Exploration Program. Aerobots are also potentially attractive for exploration of Venus, although the high temperature near-surface environment poses additional challenges to both aerobot design and operation, as we subsequently discuss. In summary, the capabilities and features of robotic airships that make them strategic platforms for planetary exploration include:

- Potential for missions with extended duration
- Very long traverse capability, achieved by employing a combination of wind-powered, long-distance passive flight with self-powered active local maneuvering
- Excellent payload to weight ratio
- High stability due to the intrinsic aerodynamic characteristics of airships, which make them resilient, stable and low vibration aerial platforms
- Capability to survey planetary areas beyond the reach of current ground systems, such as heavily featured areas, canyons, mountain ranges, volcanoes, shore lines, and liquid bodies (e.g., oceans thought to exist on Titan)
- Flight controllability, enabling precise flight path control for systematic surveying and long-term science site monitoring
- Transportation of scientific instruments and onboard laboratory facilities across vast distances, as well as soft landing, deployment and recovery of sensor pods and *in situ* laboratories at key science sites.

In general, interest in unmanned airships has been growing over the last decade, primarily for advertising, military surveillance and intelligence-gathering [10], also high-altitude communication platforms [11]. Small to medium size remotely-piloted airships are becoming commercially available, primarily for advertising. Development of autonomous robotic airships, however, is very recent. Examples include AURORA [12, 13], the subsequently-noted JPL Aerobot Autonomy project [14, 15], and LOTTE [16], which addresses airship design and flight control. Current systems use GPS-based motion control for accurate flight trajectory following. Other capabilities, particularly those related to visual navigation or long-term mission planning and execution, are in very early stages of development [17, 18].



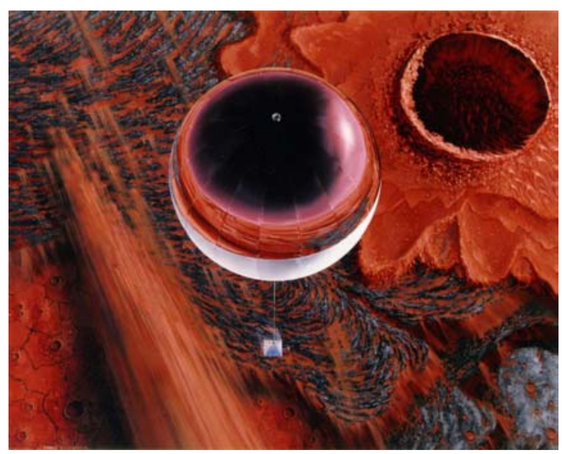


Figure 6: (left) Graphic concept for Titan aerobot mission; (right) Graphic concept for Mars balloon exploration

As regards thermo-mechanical properties and design of aerobots, such platforms can be either heavier or lighter than air. Aircraft, gliders and helicopters are examples of the former, while balloons and airships are examples of the latter. No heavier-than-air vehicle has ever flown at another planet, but two balloons did fly at Venus during the Russian/French VEGA mission in 1985 [19]. These balloons were, however, designed for near room temperature operation (~ 20 ºC) which restricted their flight to a high 55 km altitude at which the surface was obscured by the clouds. Since that time there has been limited development of balloon technology for low altitude, high temperature (460 ºC) Venus operation including balloon materials [20, 21], altitude cycling designs [22, 23] and advanced mission concepts [24, 25]. There has been a significant amount of work done on both Mars aircraft [26, 27] and balloons [28-30] with focus on packaging, aerial deployment and, for balloons, aerial inflation. Work on Titan aerial vehicles is much less advanced and has generally been limited to mission studies and conceptual vehicle designs [15, 31].

Essentially none of the non-VEGA balloon aerial vehicle technologies have been matured to flight readiness; therefore, current research activities are grappling with most of the same problems that have remained incompletely solved for the past couple of decades. At Venus, the problem of fabricating high temperature, sulphuric acid-resistant balloon materials remains paramount, but minimal R&D investments have been made in recent years. Mars vehicle development continues to be active with much recent work consisting of flight test deployment experiments conducted in the Earth's stratosphere where the atmospheric density and temperature are similar to Martian conditions. The key challenge of Martian flight is the low atmospheric density (0.015 kg/m3 on the surface) which drives the use of very lightweight but relatively fragile structural materials for aircraft and balloons, materials that are not well-suited to surviving the rigors of long-duration packaging and subsequent aerial deployment. There is some current JPL work on a Titan aerobot, which is a highly autonomous, self-propelled airship. *Figure 6* shows an artist's concept of this vehicle which is being designed to do both aerial reconnaissance and surface sampling almost anywhere on the planet over the course of a 6 to 12 month mission. The key challenges for this vehicle are development of cryogenic (90 K) balloon materials, software and avionics systems for highly autonomous operation and sampling technology. Autonomy technologies to be developed for aerobots include: accurate and safe flight control, take-off, landing and hovering; perception-based hazard detection and avoidance; local and global mapping for long-range mission planning; and science target acquisition, tracking and go-to capabilities. Furthermore, onboard autonomy architecture must integrate perception-based inferences about the environment of operation of the vehicle, vehicle health monitoring and reflexive safing actions, accurate flight control, and long-range mission planning and monitoring. Finally, navigation and flight control have to be done independently of GPS and potentially also of magnetic fields (as may be the case of Titan), requiring greater dependency on image-based motion estimation and position estimation, as well as on other absolute positioning mechanisms such as Sun or Earth sensors.

4.0 SUBSURFACE EXPLORATION BY CRYOBOT

There is substantial interest within the planetary science community to explore the Mars polar caps as well other icy bodies like the Jovian moons (Europa, Callisto, Ganymede) and Titan. The polar caps represent the primary areas where water is known or posited to exist in any great quantity. In particular, penetration of the polar caps would yield science across several fronts. By inventorying energy sources, *in-situ* instruments could infer past hydrological activity from the climate record as well as sample meltwater to look for ordered chemistry representative of past/extant micro-organism biology. Long-term trends in the Martian climate may be due to planetary obliquity excursions, global dust storms, volcanism, and hydrothermal or impact events. Subsurface ice analysis would decipher the physical and chemical records of such past climates encoded in the stratigraphy. Similarly, composition of dust-laden meltwater may reveal the evolution of sedimentary processes and volcanic contributions to that record. For science exploration to the icy Jovian moons and Titan, the focus revolves more tightly around searching for signs of life in the sub-ice ocean of Europa, and/or understanding the pre-biotic chemistry of the organic rich lakes and surrounding crater rim ice/dust material of Titan. Europa is of high interest to the science community because of its inferred inner liquid oceans below an ice sheet measuring 3-to-30 km in thickness, as determined by Galileo magnetometry data. If these oceans are heated by subterranean volcanic activity, a possibility exists that they may harbor life. Scientists have long thought that Titan, with its high volume of organic compounds and nitrogen rich atmosphere, is a prime target for a potential understanding of the building blocks and fundamental chemistry which represent the origins of pre-biotic structures very similar to what may have existed here on Earth during its early beginnings. Only by doing robotic subsurface exploration of these icy bodies will we be able to explore these theories and hypotheses.

JPL robotic mobility/sampling subsurface platform concepts being developed for Mars/Europa and Titan are the *cryobot*, and the *planetary autonomous amphibious robotic vehicle* (PAARV). The cryobot (truncation of *cryo*genic and ro*bot*) is a derivative of the original Philberth probes developed by the Army Cold Regions Research & Engineering Lab during the period 1965-to-1980. Probes built during this period used passive heating, i.e. heated surface in contact with the ice to facilitate mobility. The greatest depth achieved was 1 km in Greenland. Typically, depths were on the order of 10's to

100 m's. Instruments carried were simple temperature, pressure, and conductivity sensors. The probes maintained their vertical orientation through pendulum stabilization. This meant that the probe, hanging from its tether, automatically stabilized its orientation along its gravity vector. Philberth probes lacked on-board active navigation & control (c.f. state sensors which could transfer orientation/rate data to an on-board processor which in turn provided closed-loop GN&C and rate control), nor did they have capability to assess/manage debris in the ice. Among the biggest reliability problems with the Philberth probe was heater burn-out coupled with depth stagnation due to debris build-up in front of the nose. By comparison, the JPL cryobot is a full mobility platform that moves vertically and laterally, using differential heating of the four quadrant nose heaters and four quadrant shell heaters [32, 33]. A combination of passive heating as well as active water-jetting allows the probe to penetrate low density top ice layers (*firm-ice)*, as well as debris-laden deeper layers. The cryobot can carry up to four science instruments which enable it to image the melt column strati-graphy as it descends, and ingest melt-water sample for distribution to the micro-chemistry/organics instruments. *Figure 7* shows a prototype that recently successfully penetrated 23 m into a glacier on the Svalbard, above the Arctic Circle.

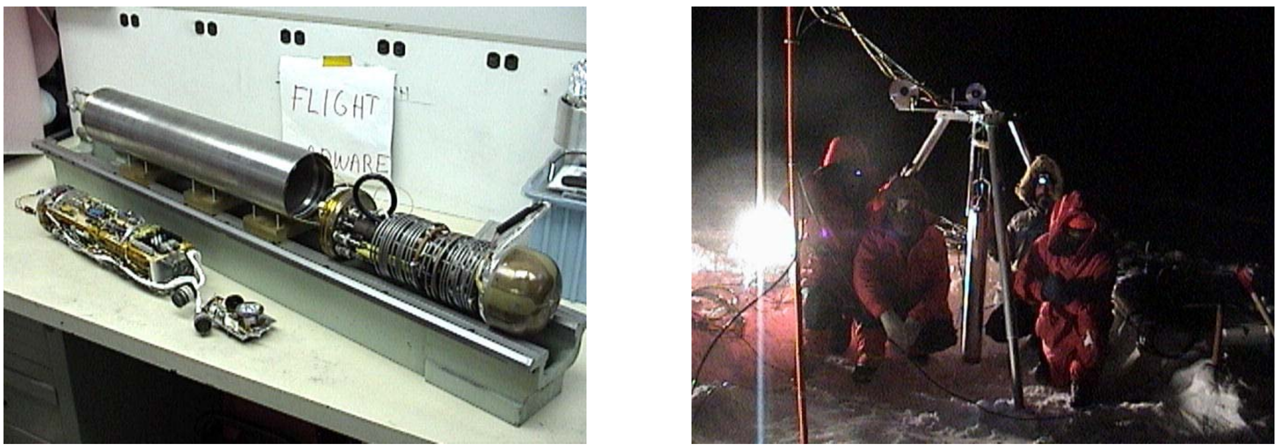


Figure 7: (Left) JPL Cryobot R&D concept vehicle; (Right) Cyrobot in operation at Svalbard, Norway, above the Arctic Circle

Moving to the PAARV, we have just recently begun to explore a concept design for an amphibious vehicle (PAARV) for Titan. As previously noted, there is significant interest in a post-2010 aerial survey of the Titan surface using a powered inflatable system. The Titan Huygens probe scheduled for deployment from the Cassini spacecraft in CY04 will sample only the Titan atmosphere as it falls to the surface. If the probe is successful and the returned science proves to be exciting, then it is possible NASA will seek a return to Titan as quickly as possible. As an extension of the Huygens atmospheric mission and in pursuit of a more detailed surface survey, scientists desire to not only sample the atmosphere close to the surface, but also sample the organic rich crater lakes and solid material at the crater rims. There are a host of applicable design concepts, studies, and trades: integrated mobility/sample acquisition systems ranging from small harpoon ballistic penetrators (not mobile), to drop-sondes lowered via tether off the aerial platform (aerial platform acts as mobility platform), to a mobile amphibious vehicle which can move under its own power to the bottom of the organic lakes and crawl up onto the lip of the crater rim. Key problems being addressed revolve around penetrator/vehicle configuration, hydro-dynamic design, power sources, tether design, ability to navigate autonomously subsurface as well as surface, sample acquisition/transfer, and selection of the *in-situ* science instrument suite. Unfortunately, existing terrestrial analogs for such technology are limited. DoD has funded amphibious vehicle research in shallow/surf mine sweeping vehicles with limited autonomy for guidance, navigation/control, and station keeping. Large ocean ROV's are currently employed by MBARI/WHOI for shallow and deep exploration. However, these vehicles are teleoperated or pre-programmed to follow a particular sweep pattern and are well outside the mass/volume design limitations associated with planetary mobile platforms. Nevertheless, it seems likely there will be some space design leverage from such areas as active buoyancy control and associated technologies such as high pressure/low temperature seals, actuators, and high strength, lightweight structural materials.

5.0 THE EVOLUTION OF SPACE MOBILITY ARCHITECTURE

Reflecting on the paper's coverage to this point, we have surveyed a wide-ranging set of space robotic mission concepts, application requirements, and possible technical solutions to recurring needs. Among the major trends are: the evolution from surface missions to surface, aerial and sub-surface domains; emphasis on outer and inner planetary missions as well as Mars; the need for increasing levels and duration of autonomy (absolutely requisite in deep space missions where time transit of Earth command links and limited data rates preclude detailed ground operations support); and needed advances in thermo-mechanical structure of space robotic design to address both environmental factors and payload packaging limitations. For mobile surface systems alone a great diversity of design and optimization is possible—in system scale, function, power, mass, traversability & terrainability—leading to both unique mission opportunities and design trades. *Figure 8* below, while by no means definitive, gives a sampling of current rover architectures and performance attributes. Some of the more extreme examples include: the JPL nanorover, a complete instrumented 2 kg flight prototype system with ambient electronics (targeted at small body and possibly Mars exploration); CMU's Hyperion, a sun-synchronous concept for long duration polar planetary mobility in the face of diurnal changes; JPL's Cliff-bot, which is in fact a closely coupled multiple robot system for cooperative cliff access; and, the previously summarized Inflatable Rover.

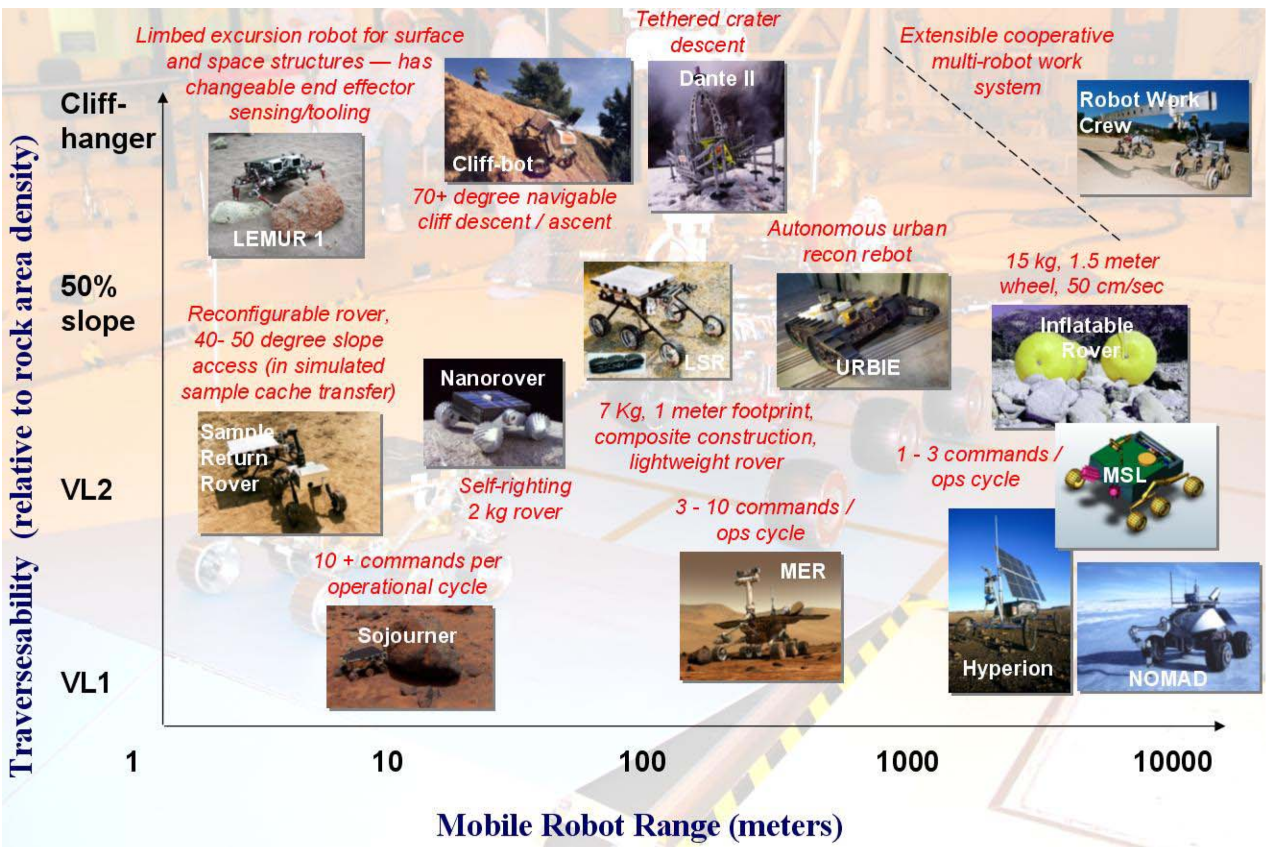
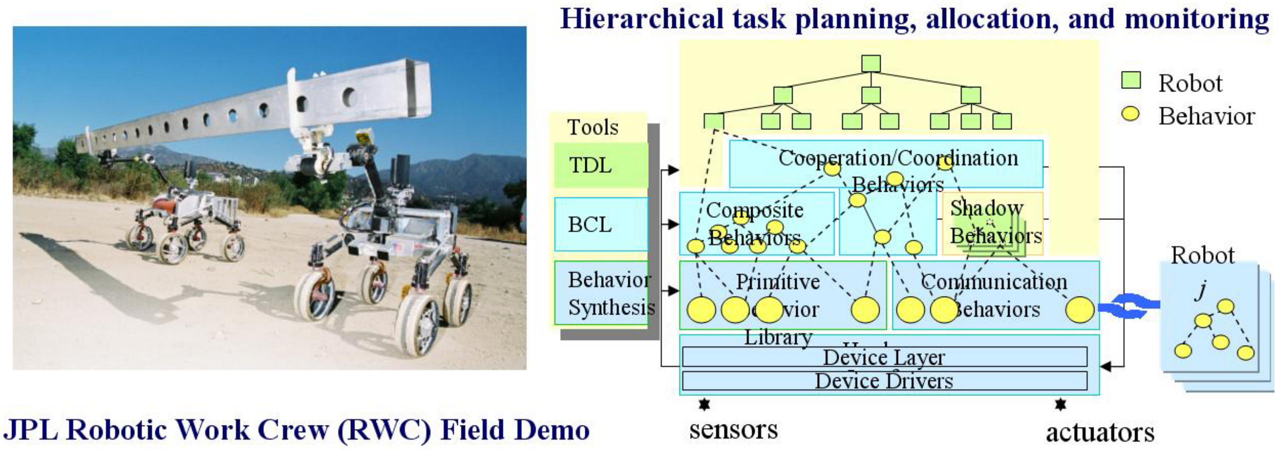


Figure 8: A sketch of some mobile surface systems in terms of their notional terrain access, operational range, and key performance parameters (NOTE: All listed attributes are approximate and for illustrative purposes only—see related open literature references for data regarding detailed performance, field experiments, and current system design maturity.)

As challenging as are the technical issues and promising the mission opportunities confronting development of future autonomous robotic explorers, there are broader vistas in mobile space robotics. Two important themes are *multi-robot cooperation* and in-space *human/robot interaction* (HRI). The first seeks the close coordination of robotic perception, planning, and action across multiple robots to implement tasks that are outside the physical and logical scale of a single robot. Automated acquisition, transport & deployment of large extended objects is one example, where that object might be a large science instrument, or an element of a science facility structure, surface power module, or modular habitat, etc.

There is a growing world-wide research effort in multi-robot cooperation, but little as yet that addresses space-relevant architectures and operational constraints, particularly high degree-of-freedom, non-holonomic real-time coordination of motion and force with minimized inter-robot communication and on-board computation in unstructured environments. We have made progress in this area with *CAMPOUT*, as highlighted in *Figure 9*. See [34, 35] and references therein.



- **<u>M</u>ixed <u>I</u>nitiative <u>C</u>ontrol <u>A</u>rchitectures support human and robot multi-agent cooperation**
- **Robots tightly, autonomously coordinate interactions to perform complex physical tasks**
- **Layered autonomy coordinates fast, reactive behaviors and higher level decisions/planning**
- **Human agent/s can be both supervisor and work team participant/s as appropriate**
- **Networked Robotics enables flexible extension, decomposition, & remapping of resources**
- **This provides capability for scaled operations over large areas and multi-task objectives**

Figure 9: A sketch of JPL's <u>C</u>ontrol <u>A</u>rchitecture for <u>M</u>ulti-robot <u>P</u>lanetary <u>Out</u>posts (CAMPOUT) and application to development of a robotic work crew for autonomous payload acquisition, transport, and deployment over highly variable, natural terrain

We have evolved this system architecture into a multi-robot design for autonomous steep terrain access and descent, as motivated by the earlier presented examples of Mars and Lunar cliff stratigraphy. See references [5, 36] for an account of our recent research and field experiments with the *Cliff-bot*, as illustrated in *Figure 8*.

The Robotic Work Crew (RWC) and Cliff-bot are exemplars for a yet broader class of systems that have their basis in *Networked Robotics* [37]. The overarching idea here is one of physically decentralized resources—sensors, computers, controllers, data structures—that can be adaptively linked into <u>distributed</u> computational modules establishing system properties. E.g., a given function, such as sensing, may be a collective (and emergent) property of the system, based in one robot agent directing the actions of another, sharing and/or fusing current state data, reaching some arbitrated control policy, etc. As a generalization, *local agents in the network can be both human and robotic*, with appropriate HRI models for conveyance of system state and control intent at sensory-motor, behavioral, and deliberative levels of action.

The above is very pertinent to the evolving frontier of space operations, which are expected become ever more global, as characterized by *increasing physical task scale, duration, levels of abstraction, and domain uncertainty*, be it model-based or anomalous. Humans and robots will necessarily cooperate closely in-space and on planetary surfaces, in both precursor missions as well as later exploration, discovery and continuing space infrastructure development. *Figure 10* sketches where we stand now technically in performing this endeavor, and what might be <u>an</u> achievable future.

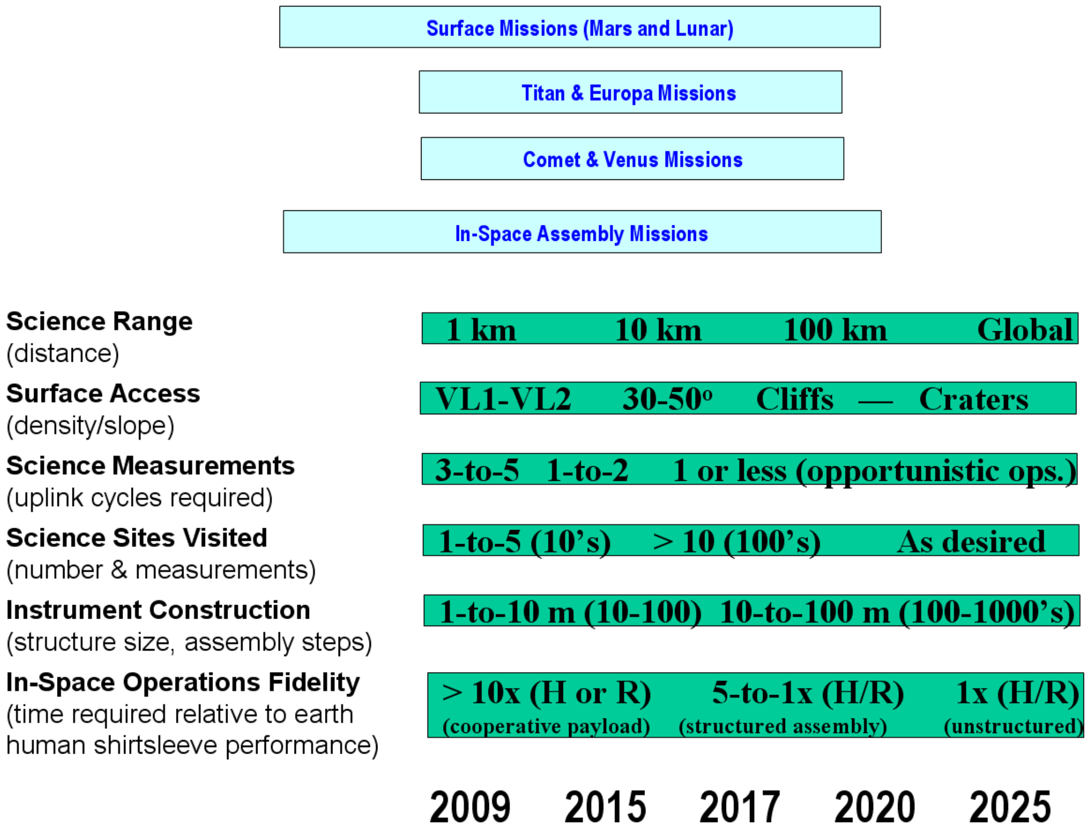


Figure 10: A conceptual roadmap for the broader evolution of space operations, in the context of autonomous and human/ robotic systems. Science range, access, measurements, and sites visited are referenced primarily to Mars autonomous rover operations. Instrument construction and in-space operations refer to prototypical orbital (or planetary surface) facility assembly, inspection and maintenance.

More specifically, and in conclusion, we suggest the following goals and objectives as an integrative technical vision for the next generation of mobile space robotic exploration:

- Rove globally over planetary surfaces and approach local sites (even in extreme terrain) within ~ 1 pixel of planning image with overall system performance comparable to a terrestrial field scientist.
- Access subsurface environments including liquid water aquifers or polar caps on Mars, Titan, Jovian moons like Europa, and penetrate through comet nuclei, and deep into lunar and Mercury polar volatiles, etc.
- Fly through atmospheres of Titan, Venus, and Mars to provide superior combinations of coverage and access where possible.
- Land safely within ~ 1 pixel of a site based on orbital imagery.
- Select, acquire and prepare samples suitable for any *in-situ* instruments with end-to-end performance comparable to current Earth science processes.
- Acquire, loft, rendezvous/capture, and return-to-Earth pristine samples within appropriate planetary protection guidelines.
- And ultimately, conduct persistent human/robotic teamed exploration of high value planetary and lunar bodies.

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